THE FEASIBILITY OF NATURAL VENTILATION IN CHICAGO'S TALL OFFICE BUILDINGS USING DOUBLE-SKIN FAÇADES

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Abstract: Thirty-one tall buildings (i.e., buildings of or taller than 200 m) have been erected to date in Chicago; 51% accounting for office function, according to the Council on Tall Buildings and Urban Habitat (CTBUH). Their energy-efficiency and healthy environment have become important concerns, given the current environmental challenges and health considerations. Many strategies in improving the properties of windows and building systems have been adopted to save energy and improve the working environment in tall office buildings in Chicago. However, only a few passive design techniques for natural ventilation have been employed. Double-skin façade (DSF) systems can provide an opportunity to apply natural ventilation strategies to tall office buildings, as they can mitigate the high wind speed and pressure through the additional skin and regulate the vertical stack flows through the segmentation. This study will investigate the feasibility of natural ventilation in Chicago's tall office buildings using DSFs. Computational fluid dynamics (CFD) simulations will be conducted to assess the performance of parametric DSF configurations, including opening size and location, cavity depth, and cavity segmentation based on indoor air velocity, indoor operative temperature, and air change rate calculated under specific climatic conditions in the simulations. These results, as related to thermal comfort and indoor airflow behavior, are important criteria for the ventilation requirements established in the ASHRAE standard. Wind tunnel tests will be conducted to validate the CFD simulation results. The DSF configuration is a key determinant of the distributions of air velocity and indoor temperature on each floor, and the proportion of driving forces between wind and stack effects. In order to assess the feasibility of natural ventilation in tall office buildings, which rely highly on mechanical ventilation, the maximum number of natural ventilation hours throughout the year in Chicago will be predicted based on the analysis of the simulation results and the weather data. The proper DSF configurations with quantified natural ventilation will lead to a better understanding of how DSFs should be designed for tall office buildings and provide a performance-based design guideline for the early design stage in which iterative and rapid design decisions are made.

Keywords: Double-skin façade, natural ventilation, tall office building, CFD simulation

1. INTRODUCTION

1.1. ENVIRONMENTAL CHALLENGES AND HEALTH CONSIDERATIONS

The City of Chicago is the home to tall buildings, the birthplace of the skyscraper, and one of the first places in which the innovative design and engineering of tall buildings emerged. According to the Council on Tall Buildings and Urban Habitat (CTBUH), there are thirty-one tall buildings (i.e., buildings of, or taller than, 200 m) to date in Chicago. More than half of them are dedicated to office functions. Four more tall buildings are expected to be completed in the next three years (CTBUH 2019). Increasing urban population, increasing land prices, green land preservation needs, global competition, and emerging technologies contribute to this trend in cities (Sev and Aslan 2014). Most tall office buildings rely highly on mechanical systems and consume extensive amounts of energy compared to other types of buildings. In climate zone 2, including Chicago, as defined by U.S. Energy Information Administration (EIA), 35% of total energy consumption is responsible for HVAC systems in commercial buildings by end use (EIA 2002). The total amount of electricity consumed in commercial buildings has consistently increased over the years, due to the use of new types of electronic equipment and existing technologies such as computers, office equipment, and so on (EIA 2012). The use of these electronics can lead to more electricity consumption due to additional cooling loads and ventilation equipment. In addition to energy consumption in tall office buildings, the sealed tall office building, relying on mechanical ventilation, can cause Sick Building Syndrome (SBS), which consists of various nonspecific symptoms. According to some studies, SBS symptoms are correlated with insufficient ventilation. Moreover, insufficient ventilation can cause occupant health problems and the decrease in occupant productivity (Sundell et al. 2011; Fisk et al. 2012). Therefore, the energy-efficiency and healthy environment of tall office buildings have become important concerns, given the current environmental challenges and health considerations.

1.2. CHALLENGES TO FACILITATE NATURAL VENTILATION IN TALL OFFICE BUILDINGS

It is still a challenge to apply natural ventilation to tall office buildings due to the strong winds and the fluctuations that are possibly experienced at upper floors, the possible extreme stack flows, and the deep lease span determined by economic, floor planning, and structural aspects.

Although there are some naturally ventilated tall office buildings, only narrow, operable windows with perforated panels are implemented in most cases, due to the strong winds (based on the case studies in Wood and Salib 2013; Li 2012). Theoretically, if the average wind speed at 10 m is 4.47 m/s (i.e., the windiest months on average in the Chicago area), the average wind speed at 300 m is about 11.58 m/s based on the log wind profile equation. Only a few naturally ventilated tall office buildings with double-skin façades (DSFs), taller than 200 m, have been developed (e.g., Commerzbank Tower in Frankfurt, Germany). Effective natural ventilation requires the buildings to have narrow lease spans, atriums, and solar chimneys that may not be preferred for the design of tall office buildings due to the initial construction costs, the loss of rentable space, structural aspects, etc. Thus, most of the naturally ventilated tall office buildings with DSFs are still shorter than 200 m based on the information collected from available databases (BestFacade, Japan Sustainable Building Database), online sources (ArchDaily), and studies (Lee et al. 2002; Oesterle et al. 2001; Poirazis 2004). The indoor airflow behavior affected by multi-story DSF components in naturally ventilated tall office buildings taller than 200 m has not been fully investigated, as predicting the airflow behavior and quantifying natural ventilation are challenging due to the possible fluctuating wind speed and direction around tall buildings.

The height of tall buildings possibly causes extreme stack flows with respect to the large pressure differentials between the top and the bottom (Wood and Salib 2013) and thus, the unfavorable stack flows can also take place in the extensive cavity of multi-story DSFs. These stack flows in the cavity may cause occupant discomfort when the windows on the inner skin are open. Further, the stack flows may deliver overheated cavity air to the upper floors, which affects the indoor temperature of the adjacent spaces possibly requiring additional cooling loads. According to some studies (e.g., Gratia and Herde 2007; Wong et al. 2008; Larsen et al. 2015), DSFs may cause overheating problems as the façade is highly glazed and the absorbed heat from solar radiation may be retained in the cavity. Only a few studies (e.g., Wong et al. 2008; Nasrollahi and Salehi 2015) considered wind effect as a driving force, which not only improves the airflow in the cavity, but also removes the heat from it. Therefore, wind effect can be harnessed to facilitate natural ventilation and reduce overheating problems. However, due to the potential magnitudes of driving forces generated by wind and stack effects in tall buildings, the façade design of tall buildings entails more challenges than low rise buildings (Etheridge and Ford 2008). Therefore, the balance between stack and wind effects in the cavity can be a key determinant of effective natural ventilation in tall office buildings with DSFs. The segmented cavity of DSFs should be carefully considered to avoid possible discomfort at upper floors of tall office buildings with respect to overheating and stack flows.

Narrow plan width is one of the typical features of naturally ventilated buildings, including floor-to-ceiling heights of approximately 3 m, good solar control, high thermal capacity, and well-designed adjustable openings (CIBSE 2005). There is no specific standard for the lease span of tall buildings, but some studies suggested the range based on case studies. According to a study by Cho (2007), 80 % of high-rise office buildings have a lease span of 10 to 15 m. The depth of the lease span should be between 10 m and 14 m for office functions due to economic aspects, floor planning, and structural requirements (CTBUH 1995). CIBSE applications Manual A10 suggests wind-driven ventilation strategies with respect to the ratio of floor width (W) and height (H): (1) Single-sided ventilation with single opening ($W \leq 2H$), (2) Single-sided ventilation with double opening ($W \leq 2.5H$), and (3) Cross ventilation ($W \leq 5H$) (CIBSE 2005). However, the proper depth of lease span for effective natural ventilation in tall office buildings with DSFs may not be determined by the requirements and the suggestions mentioned above due to the combined effect of two main driving forces, such as wind and stack effects in the cavity.

2. OBJECTIVES

This study will investigate the feasibility of natural ventilation in Chicago's tall office buildings using DSFs. This study will specifically: (1) quantify the natural ventilation performance of a tall office building with DSFs by conducting computational simulations and wind tunnel tests. Quantifying the performance is important to understand the indoor airflow behavior and the complicated heat transfer that takes place in the cavity and the adjacent indoor spaces, (2) assess the performance of parametric DSF configurations, including opening size and location, cavity depth, segmentation based on indoor operative temperature, indoor air velocity, air change rate, and the number of natural ventilation hours under the specific climatic condition in Chicago, and (3) develop a performance-based DSF design guideline that can be used in the early design stage. Passive strategies should be discussed earlier in the design process, as they can considerably affect building forms, structures, materials, and systems.

3. METHODOLOGY

The natural ventilation performance of tall buildings with DSFs is dependent on the complex heat transfer and the airflow behavior in the cavity and adjacent indoor spaces. These not easily predictable phenomena are highly informed by the outdoor conditions and the DSF configurations. Accordingly, proper assessment and prediction tools are required to effectively evaluate the feasibility of DSF applications in tall office buildings, as well as the performance of DSFs in the early design stage. If available, full-scale experiments are more desirable than other methods, such as analytical methods, empirical methods, and reduced-scale experiments, since they generate the data closest to reality. Full-scale measurements were conducted to validate computational simulation results in some studies on the performance of DSFs (e.g., Kim et al. 2011; Wen et al. 2017). As a reduced-scale experiment, wind tunnel tests have not been commonly conducted in the studies on DSFs compared to full-scale experiments and computational simulations. Only a few studies (e.g., Hu et al. 2017) investigated the impact of DSF configurations, such as cavity depth and openings, on the distribution of wind pressure over the surfaces of tall buildings with respect to structural aspects.

3.1. CHOSEN RESEARCH METHODOLOGY

Computational Fluid Dynamics (CFD) can be utilized to make comprehensive predictions on natural ventilation in buildings, as it provides the distributions of air velocity, temperature, pressure, and particle concentration. As an evaluation and prediction tool for natural ventilation, the reliability of CFD has been proved in many studies (e.g., Cheung and Liu 2011; Brandl et al. 2014). These studies conducted CFD simulations and validated the CFD results against either data from on-site measurement or experimental measurements available in the literature. CFD simulation is a relatively promising method and widely used in various studies on DSFs. CFD simulations have been conducted to investigate the impact of design parameters of DSFs such as the variations of openings (Nasrollahi and Salehi 2015), cavity width/height (Sanchez et al. 2016), and shading devices (Su et al. 2017). CFD provided various visual and quantified results such as indoor air temperature, indoor air velocity, cavity temperature, airflow rate, and air change rate for these studies depending on what results each study expected to obtain. Once validated, CFD can provide more detailed airflow characteristics on the entire space than experimental methods, which only provide the data for some points (Omrani et al. 2017). Therefore, the coupling method of CFD and experiments has been commonly used for parametric studies on natural ventilation in buildings with DSFs, as the iterative process in terms of modifying parameters can be conducted in the computational domain after the validation of CFD simulation results against experimental data. Although full-scale experiments generate more realistic data, in this study, wind tunnel tests will be conducted to validate the CFD simulation results, due to the lack of experimental data for the analysis of naturally ventilated tall office buildings (i.e., buildings taller than 200 m) with multi-story DSFs.

3.2. SELECTED CITY AND CLIMATE

Chicago was selected to improve the relevance of this research to practice, as it has more tall buildings than other cities in the world according to CTBUH (CTBUH 2019) (i.e., thirty-seven 200m+ tall buildings in Chicago). Moreover, a few DSFs have been applied only to low and mid-rise buildings in Chicago. Most DSF applications are found in European cities in which there are a few tall buildings, based on the available information from (BestFacade, Japan Sustainable Building Database), online sources (ArchDaily), and studies (Lee et al. 2002; Oesterle et al. 2001; Poirazis 2004). Since the climate of Chicago is classified as Cool-Humid (Zone 5A) (ASHRAE standard 90.1-2010 and 169-2013), Chicago may represent such cities as Boston, New York, and Seoul. According to the State Climatologist Office for Illinois, Chicago's climate is continental with cold winters, warm summers, and moderate spring and fall. Temperature, humidity, cloudiness, and wind direction are frequently fluctuating within a short range. There are several features of the climate of Chicago. The strong winds in Chicago can be experienced between tall buildings. A frequent lake breeze also affects the climate of Chicago. Wind speeds, in central and northeastern Illinois in which Chicago is located, are higher than western, northwestern, and southern Illinois due to the flat and open terrain with barely any trees and hills. More moderate temperatures in spring and fall are the norm in Chicago; on the other hand, wind speeds are higher in spring and winter (State Climatologist Office for Illinois). Therefore, natural ventilation may be more suitable during spring and fall, yet it could be also suitable for some buildings along the shore of Lake Michigan in summer, due to the breeze.

3.3. DESIGN PARAMETERS

There are various design parameters that were already investigated to assess the performance of DSFs. Some key findings related to design parameters are emphasized in some studies on DSFs: the relationship between cavity temperature and opening size (Gratia and Herde 2007), the recommendations for opening location to improve the airflow throughout the entire building (Nasrollahi 2015 and Salehi 2015), the optimum air cavity width/height to reduce energy consumption in the summer and winter scenarios (Sanchez et al. 2016), the effects of cavity extension on the airflow inside the cavity as the way of preventing reverse flow (Barbosa 2015), the importance of shading devices for the thermal performance of DSFs (Mei et al. 2007), and the impact of glazing type/position on building cooling energy (Chan et al. 2009). The results and conclusions from these studies are helpful for architects to have an initial idea of how DSFs should be conceptualized in the early design stage. Among various design parameters mentioned above, the more fundamental and wind-related components, such as openings, cavities, and segments, are the only ones tested in this study, as wind effect is one of the most important factors for effective natural ventilation in tall office buildings with DSFs.

A 238 m (780 ft) hypothetical tall office building model is developed for this study. The model consists of sixty floors with the floor depth of 36 m (120 ft) and the lease span of 9 m (30 ft). The ratio of building height and depth is preferably 6:1 (Choi 2009). The floor to floor height is 4 m (13 ft) with the ceiling height of 2.7 m (9 ft) in the consideration of the steel structure. Due to the insufficient information on the components of DSFs for tall office buildings taller than 200 m, the range of variations of DSF components is determined based on the existing buildings investigated by Wood and Salib (2013). As it is shown in figure 1, the design parameters such as cavity depth, cavity segmentation, and opening size and location will be tested in the CFD simulation software ANSYS FLUENT. As one of the expected

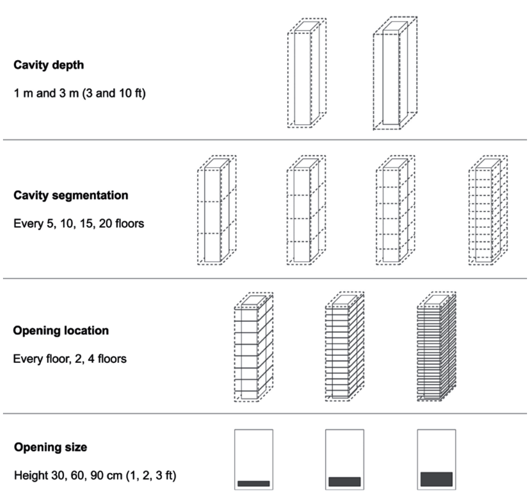

Figure 1: Design parameters and variables defined for simulations. (Author 2019)

results in this study, the combined effect of those design parameters on natural ventilation in tall office buildings with DSFs will be discussed, as the parameters affect both stack effect and wind effect, two important driving forces for natural ventilation. Moreover, the results will show which parameter is the most influential in facilitating effective natural ventilation and in optimizing the magnitude of the two driving forces.

3.4. RESEARCH WORKFLOW

As it is shown in figure 2, the workflow consists of several steps with respect to the simulation, the experiment, and the assessment process. CFD is the main tool to simulate the performance of DSF configurations under specific climatic conditions, including outdoor temperature and wind profiles within the atmospheric boundary layer (ABL). Wind tunnel tests will be conducted to simulate the airflow in some configurations and compare the data with the CFD simulation results for validation. Due to the time intensive nature of the simulation process, resulting from the size of the computational domain and the 3D model (i.e., a tall office building with DSFs), the CFD simulation process is divided into three parts, such as 'outdoor simulation', 'indoor simulation—cavity only', and 'indoor simulation—typical floor'. There are basically seventy-two naturally ventilated tall office building models with DSFs to be tested in the CFD simulation. The performance of each configuration will be assessed at the end of the workflow based on the ventilation requirements.

Task 1: Outdoor Simulation

First, a large computational domain is created to simulate outdoor conditions and obtain data as realistic as possible. Since tall buildings dynamically respond to wind according to the characteristics of turbulent flows depending on the height, simulating the whole building with the outdoor conditions in the computational domain is inevitable, in order to reduce the discrepancies between the simulation and the reality (figure 3a). The airflow will be simulated only for the outside of the building to obtain boundary conditions, such as wind velocity and outdoor temperature on the outer skin of DSFs. A few tall office buildings with DSFs will also be physically modeled in accordance with the wind tunnel environment. The CFD simulation results obtained from this first step of the CFD simulation process will be compared with the wind tunnel data only for validation of the impact of the outdoor conditions on the surfaces of the tall office building.

Task 2: Indoor Simulation – Cavity Only

Second, the boundary conditions collected from the first step of the CFD simulation process will be used to

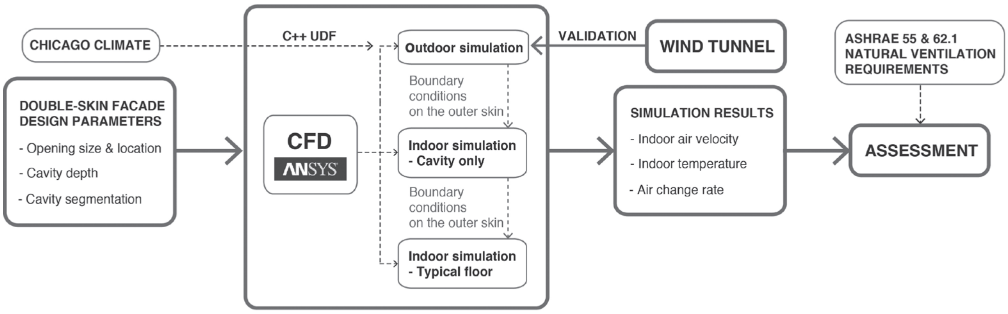

Figure 2: The overall workflow: CFD simulation and wind tunnel test. (Author 2019)

simulate the distributions of velocity and temperature in the cavity, without any air movement between the cavity and the adjacent indoor spaces. Thus, operable windows are not created on the inner skin in this step of the process. As illustrated in figure 3b, the multi-story DSF type was chosen for this study as sufficient vertical force can be used to drive air through the vertically continuous cavity. However, in this study, the cavity is segmented into several zones as the extensive cavity of tall buildings may cause extreme stack flows, due to the height. The objectives in the second task are to (1) preliminarily assess the performance of DSF configurations with respect to the complex airflow characteristics inside the cavity, and (2) obtain all the boundary conditions on the inner skin to simulate the airflow in the indoor spaces as the next step.

Task 3: Indoor Simulation – Typical Floor

Third, the indoor airflow on some typical floors (e.g., one floor within each segment) will be simulated to obtain the detailed information on airflow characteristics such as the distributions of air velocity and indoor temperature on the floors, and also air change rate based on the airflow through operable windows on the inner skin. For the CFD simulation, only the indoor spaces are created without DSFs (figure 3c), as the external environment and the cavity are already accounted for in the previous simulation steps. In order to investigate the impact of the wind direction and the related pressure on ventilation types such as single-sided and cross-ventilation, the distribution of wind pressure on four-sides of the square floor plan will be simulated simultaneously with different boundary conditions for each side. The performance of each configuration will be assessed based on whether the indoor spaces with each configuration meet the ventilation requirements established in ASHRAE standards: (1) Indoor air velocity should not exceed 0.2 m/s (ASHRAE standard 55-2010), (2) Indoor operative temperature should be within the acceptable range based on the chart, 'Acceptable operative temperature ranges for naturally conditioned spaces' in ASHRAE

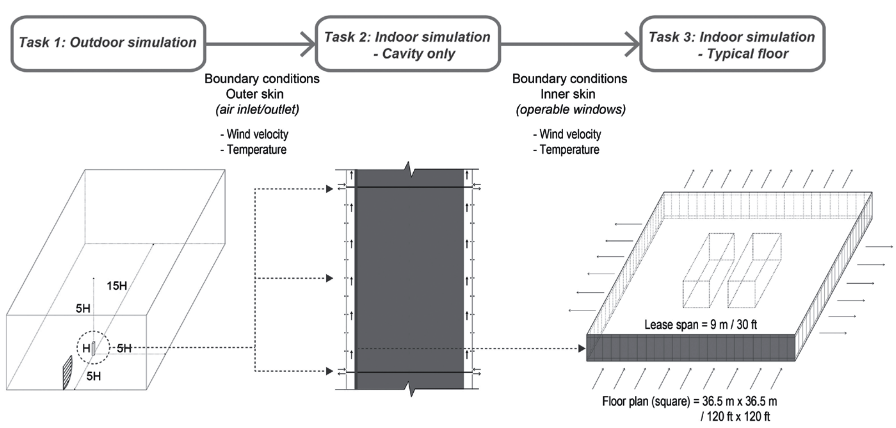

Figure 3: (a) A tall office building with DSFs in the CFD domain, Source: (Franke et al. 2004), (b) one segment, a part of the whole building section with DSFs, and (c) A typical floor plan and the wind direction with positive and negative pressure. (Author 2019)

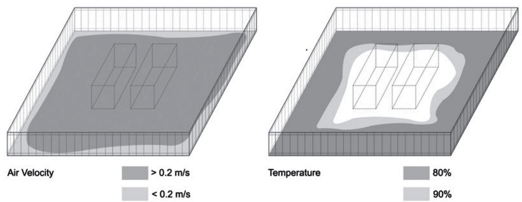

Figure 4: An example of visualized air velocity and temperature distributions. (Author 2019)

standard 55-2010, and (3) Air change rate is required to be 6-8 exchanges per hour (ASHRAE standard 62.1-2013). After the assessment of the DSF configurations and the interpretation of the results based on the criteria, some more configurations with modified design parameters may need to be tested again from the second step of the CFD simulation process to find better configurations for the indoor airflow behavior. The possible variations of lease span will be also discussed in this task, based on the simulation results.

4. EXPECTED OUTCOMES

The CFD simulation is currently being conducted to obtain the results and key findings. Thus, at this point, the expected results from both the CFD simulation and the wind tunnel test are discussed in this section. This research is expected to produce the following: (1) the visualized distributions of air velocity and indoor temperature at 1.2 m and 1.8 m above the floor (i.e., occupied zone) to determine the acceptability of thermal comfort and the effectiveness of natural ventilation in the indoor spaces (figure 4), (2) the most proper double-skin façade (DSF) configuration with quantified natural ventilation performance to facilitate effective natural ventilation in tall office buildings in Chicago and other cities that have similar climatic conditions, (3) the maximum number of natural ventilation hours throughout the year in Chicago, (4) a performance based DSF design guideline, for the design of openings, cavities, and segments, which can be used in the early design stage, (5) the reasonable lease span of tall office buildings for effective natural ventilation, and (6) the suitable proportion between the magnitude of stack effect and wind effect inside the cavity depending on the height (e.g., a comparison between the proportion in the cavity near lower floors and higher floors).

5. CONCLUSIONS

The conclusions are expected to address the feasibility of natural ventilation in Chicago's tall office buildings, by means of DSFs, which currently highly rely on mechanical systems. As one of the expected results, the proper DSF configurations will lead to a better understanding of how DSFs should be designed not only to facilitate effective natural ventilation, but also to improve thermal comfort in indoor spaces under the specific climatic conditions in Chicago. The performance-based DSF design guideline will help architects and designers make decisions in the early design stage when passive strategies should be discussed, as they significantly affect building forms, structures, materials, and systems. Further insight on the airflow behavior in Chicago's tall office buildings with DSFs will enable one to specifically determine the size and the location of DSF components for each floor, based on different magnitudes of stack and wind effect. Although the energy performance of tall office buildings with DSFs is not quantified in this study, the application of natural ventilation is expected to improve the energy performance by reducing the load on HVAC systems. Despite the large number of tall office buildings, DSFs have not been applied to any tall office buildings in Chicago, due to the initial construction costs, additional maintenance costs, the loss of rentable space, and structural loads, etc. However, if proved, the benefits of DSFs for natural ventilation, energy performance, and thermal comfort may compensate for the disadvantages.

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